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APPLICATION OF ACOUSTIC EMISSION TECHNIQUE FOR ONLINE MONITORING OF FRICTION STIR WELDING PROCESS DURING WELDING OF AA6061-T6 ALUMINUM ALLOY

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Abstract

Acoustic Emission (AE) technique has been successfully used to monitor processes like metal cutting, grinding and electron beam welding as a nondestructive evaluation method. Friction Stir Welding (FSW) is a solid state welding that avoids problems associated with fusion welding and is used in aerospace industries. An attempt has been made to study the application of AE technique to monitor FSW process by identifying the occurrence of defect while welding is in progress and suggest means to rectify the defect. In this study, aluminum alloy AA6061-T6 has been used as work piece material. It was observed that the nature of AE signals produced during welding are helpful in identifying the occurrence of defects produced. The values of a few AE parameters derived from AE signals were found to be helpful in developing a model for online monitoring of FSW process to produce defect free welds. The model has been successfully validated.

Introduction

FSW is a solid–state, hot–shear joining process invented at The Welding Institute (TWI), United Kingdom in 1991. The schematic diagram of the process is shown in Figure.1 [1] in which a rotating tool with a shoulder terminating in a pin with a particular geometry which moves along the butting surfaces of two rigidly clamped plates placed on a backing plate.

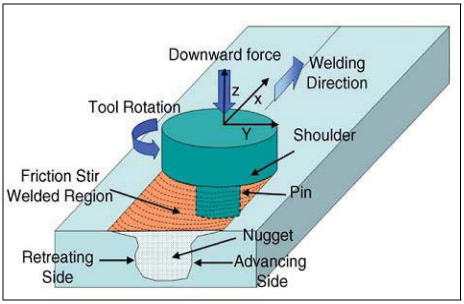

Figure 1. Schematic diagram showing the working principle of FSW [1-3]

The shoulder makes firm contact with the top surface of the work piece. Heat generated by friction at the shoulder and to a lesser extent at the pin surface softens the material being welded. Severe plastic deformation and flow of this plasticized material occurs as the tool is translated along the welding direction [2-3]. Material is transported from the front of the tool to the trailing edge where it is forged into a joint due to a small tilt provided to the rotating tool. The half–plate where the direction of rotation is same as that of welding is called the advancing side, while the other side designated as retreating side. Since its discovery FSW has evolved as a technique of choice in the routine joining of aluminum components, its applications for joining different metals other than aluminum are also growing, although at a slower pace [4]. In FSW, the important process parameters which affect the quality of weld are tool rotational speed, weld traverse speed, axial force resulting from shoulder deepness inserted into surface of the base metal (plunge depth) and tool tilt angle.

Authors in their earlier studies made investigation on the role of tool pin profile on tensile strength of welded joints by considering the important FSW parameters like (i) Tool rotational speed, (ii) Weld traverse speed and (iii) Plunge depth [5].

Acoustic Emission is the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or source within a material, or the transient elastic wave generated when a material undergoes deformation [6]. Acoustic Emission technique is a non –destructive technique which is different from other non- destructive testing techniques in two regards: (i) it pertains to the origin of the signal. Instead of supplying energy to the object under examination, AE technique simply listens for the energy released from the object followed by amplification and quantification of AE signals. AE tests are often performed on structures while in operation, as this provides adequate loading for propagating defects and thereby triggering AE and (ii) AE testing deals with dynamic processes or changes in a material. This is particularly meaningful because only active features (e.g. crack growth) are highlighted [7]. An advantage of using AE technique as a process monitoring tool is that the frequency range of AE is much higher than that of machine vibrations and ambient acoustic noise. Sources generating AE in different materials are unique due to properties of materials [8].

Beattie et.al conducted AE tests on aircraft Halon Fire Bottles to determine the presence of cracks based on AE counts [9]. Shiroishi et.al investigated defect detection methodologies for rolling element bearings through sensor signature analysis [10]. Dunegan used the AET for measuring surface roughness. RMS or the Average Signal Level (ASL) of the AE signal generated was used for understanding of the process and measurement of roughness [11]. Craig et.al in the review of the smart metallic structures program, focusing on the health monitoring system architecture (specifically the sensors, processors and analysis algorithms contained therein), investigators used AE and fiber optic sensors to provide damage detection and strain monitoring in metallic structures [12]. Lee et.al studied the tensile behavior of low carbon steel welds by means of AE Technique. During the study the AE characteristics were observed at base metal, heat affected zone and weld metal of welded joint. The main AE parameter, AE energy rate was measured during the tensile tests. [13]. Miettinen et.al used AE in monitoring of extremely slow rotating bearings [14]. Beggan et.al used AE to predict surface quality. During their study AE signals were used to monitor tool wear and tool breakage thereby correlate with surface quality [15]. Jaap H.HEIDA et.al made investigation into the applicability of the AE and ultrasonic inspection technique for the monitoring of cure related defects in thick resin transfer molded products. [16]. J. Kopač et.al studied the use of AE during drilling of carbon C15E steel and nodular gray iron (G40). During the study they performed tool wear monitoring of drilling process [17]. Akop'yan et.al made studies on correlation between parameters of AE signals and degree of corrosion damage in Aluminum Alloys [18]. Xiaozhi Chen et.al used AET for tool condition monitoring based on wavelet analysis. Studies were made using tungsten carbide tool to machine mild steel [19]. Sundaram et.al used AET in the study of geometry of flank wear in single point cutting tool [20].

Authors in their earlier studies have established the applicability of Acoustic Emission technique to monitor FSW process. During establishing the relationship between FSW input process parameters and output AE parameters one of the FSW process parameters were varied continuously and AE signals were recorded. It was observed that as the FSW parameters varied the pattern of AE signal were also varied [21]. It has been observed from the literature that AE technique has been successfully adopted in many fields, namely laser welding, health monitoring of aerospace structures, study of tool wear during drilling, turning, milling, etc. However, it has also been observed that, there is little published information available about the use of AE technique to monitor FSW process online by identifying the occurence of defects during the FSW process followed by suggesting corrective action. The authors in their earlier work have concluded that there is sudden increase in the values of AE parameters namely RMS, Amplitude, Energy whereas there is sudden decrease in the value of counts whenever there is occurrence of defect. This has been verified by comparing the X- Ray radiography image and pattern of AE signals [22]. In this study an attempt has been made to monitor FSW process online and to develop a model for online monitoring of FSW by analyzing the AE parameter derived from AE signals generated during welding. The developed model for online monitoring of FSW process has been used to produce defect free welds.

Experimentation

Experimental work comprises of four stages: (i) Conduction of experiments and sensing of AE signals during welding (ii) Study the behaviour of AE parameters derived from AE signals during welding, (iii) Development of a model based on threshold values of AE parameters to distinguish between bad and good welds categorized based on the presence or absence of defects and (iv) validation of model.

The base material used in this study is Aluminum alloy AA6061-T6. It is magnesium based alloy and widely used in construction of aircraft structures, such as wings and fuselages, more commonly in homebuilt aircraft than commercial or military aircraft. Aluminum Plates of 5 mm thick were cut to a dimension of 300 mm × 75 mm with square edges to prepare butt joint. Plates were fixed firmly on the FSW machine using suitable clamps. Welding was carried out using conical threaded tool made out of oil hardened steel. Based on the similar lines of experiments conducted earlier by the authors the optimal values of process parameters selected used in this study are tool rotational speed of 700 rpm, traverse speed of 63 mm/ min and plunge depth of 4.85 mm [5]. Three welds were prepared for the optimal process parameters and AE signals were recorded.

AE sensor (Wide band, Piezoelectric transducer, operating frequency: 100 kHz – 2000 kHz, gain: 40 ±1dB) was mounted on the work piece by using a suitable couplant followed by connecting the sensor cable to computer through preamplifier with band pass filter (Gain-40 dB, filter: 125 kHz - High Pass). The location where the sensor was fixed was confirmed by Hsu-Nielsen method as per ASTM E 976-05. AE data was acquired for the selected FSW input process parameters and stored in the computer using AE data acquisition system setup (make:

MISTRAS, Physical Acoustic Corporation, USA) as shown in Figure 2 and processed to determine various AE parameters using AEwin software. The important AE parameters considered during the study are RMS, Energy, Amplitude and Counts. Welded joints were subjected to X- Ray radiography test to locate the position of defects produced during welding. Tensile specimens were prepared as per ASTM - E8 / E8M-08 standard by choosing the portion of the welded joint where there were no defects revealed from X –Ray radiography image. Tensile test was carried out using Electronic Tensometer (model: PC 2000, make: Kudale Instruments, Pune).

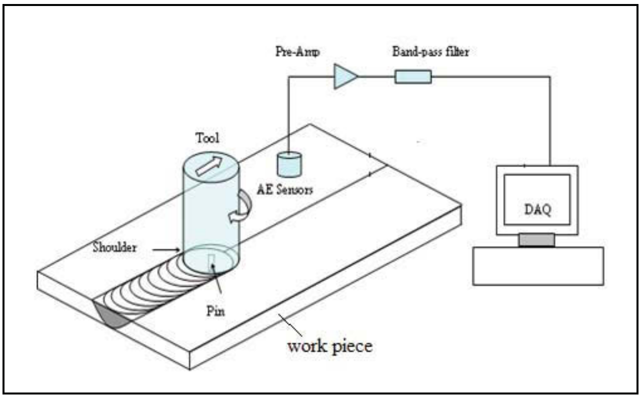

Figure 2. Schematic diagram showing FSW with AE data acquisition system (Courtesy: MISTRAS, Physical Acoustic Corporation, USA)

Results and discussion

The photographs of FSW joints prepared for the selected optimal process parameters are shown in Figure 3, 4 and 5 respectively.

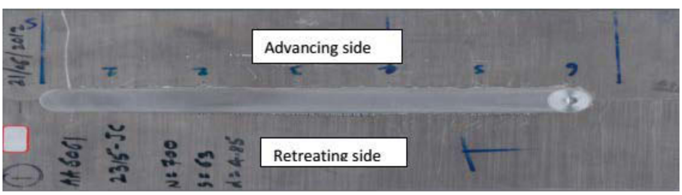

Figure 3. Photograph of FSW joint (Weld 1)

Figure 4.Photograph of FSW joint (Weld 2)

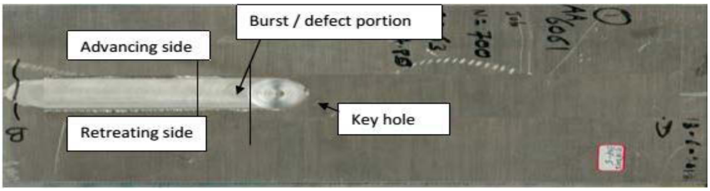

Figure 5. Photograph of FSW joint (Weld 3)

In this study the time taken for complete plunge and dwell is about 40 sec. After plunging the tool traverses with the set speed resulting in welding till the preset length of 200 mm weld is obtained. X-Ray radiography test showing no defects in the weld 1 and weld 2. Further there is no sudden increase in RMS, Amplitude and energy and sudden decrease in counts observed during the preparation of weld 1 and weld 2 revealing non occurence of defect. The screen shots of AE signal pattern of AE parameters acquired in preparation of weld1 and weld 2 are shown in Figure 6 and 7 respectively. It was observed that the RMS, Energy, Amplitude and Counts were found to vary marginally during 20 to 160 sec of welding for weld 1 and during 30 to 160 sec of welding for weld 2. It was observed that while preparation of weld 3, between 40 sec and 50 sec that there was a sudden increase in RMS, Energy, Amplitude and sudden decrease in Counts revealing in occurence of defect. This has been shown as encircled marks of screen shot of Figure 9.The details of variation in AE parameters, average tensile strength along with joint efficiency at non defect region of welds of AA6061-T6 are presented in Table I. Based on the minimum and maximum values of AE parameters(Table I), higher and lower threshold limits were set to identify formation of good and bad welds are presented in Table II. Based on the above discussion and as per the methodology adopted by the authors in their earlier work using AA6082-T4 Aluminum alloy an Online FSW Monitoring System (OLFSWDMS) model has been developed for AA6061-T6 Aluminum alloy is as shown in Figure 9 [22].

Table I Values of AE parameters showing maximum and minimum values along with joint efficiency for aluminum alloy AA6061-T6

Weld No.	RMS(v)		Energy x1000		Amplitude (dB)		Counts x1000		Average Tensile strength (N/mm^2)	Efficiency (%)
	Min	Max	Min	Max	Min	Max	Min	Max		
1	0.15	0.33	10	32	78	84	22	24	189.20	80.16
2	0.09	0.11	11	15	71	78	18	22	161.50	68.40
3	0.12	0.78	26	46	77	98	22	26	201.00	85.10

Table II Values of threshold limits of AE parameters for aluminum alloy AA6061-T6

	AE parameters			
	RMS (v)	Energy x1000	Amplitude (dB)	Counts x 1000
Higher threshold limit	0.33	46	85	26
Lower threshold limit	0.12	10	71	18

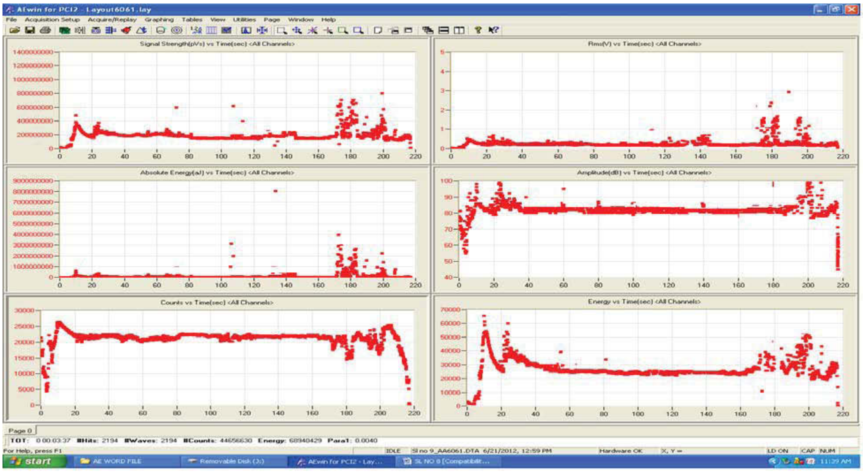

Figure 6. Screen shot showing AE signal pattern of different parameters during welding (weld 1)

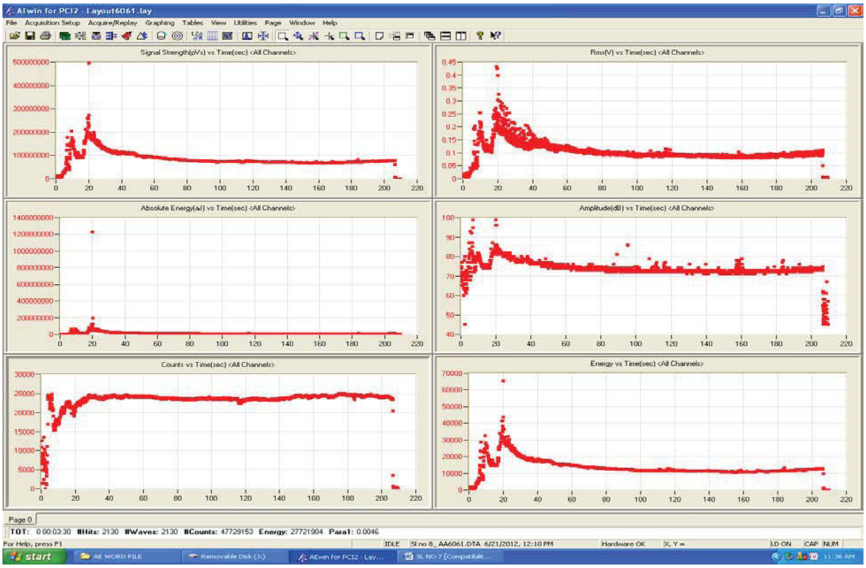

Figure 7. Screen shot showing AE signal pattern of different parameters during welding (weld 2)

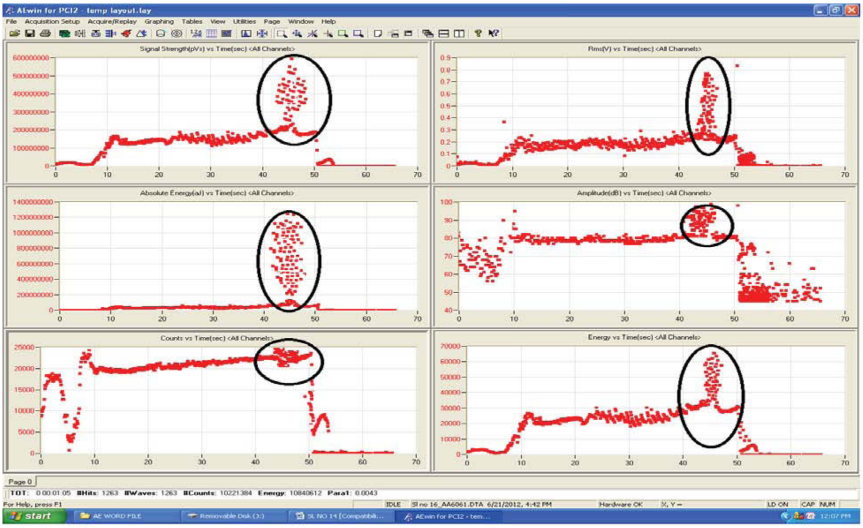

Figure 8. Screen shot showing AE signal pattern of different parameters during welding (weld 3)

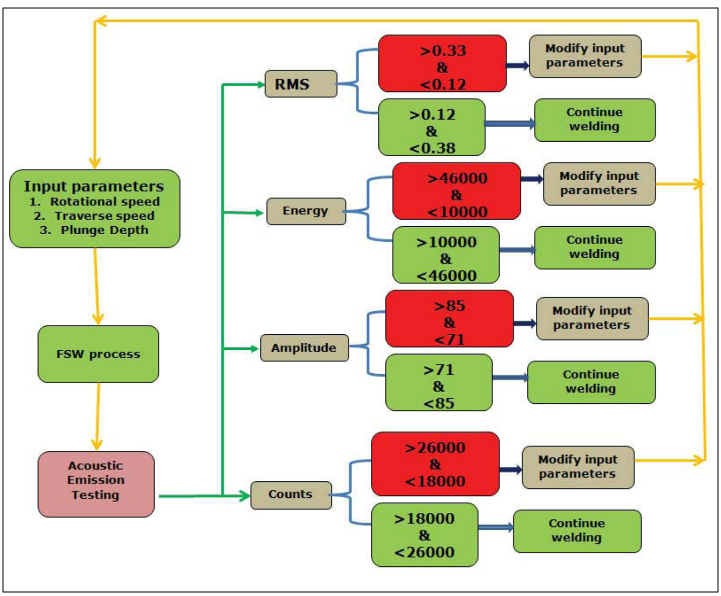

Figure 9. OLFSWMS model showing necessary action to be taken

Validation of OLFSWMS model

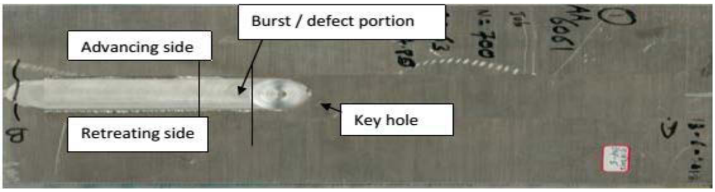

Figure 5(a). Photograph of FSW joint (non retraced -Weld 3)

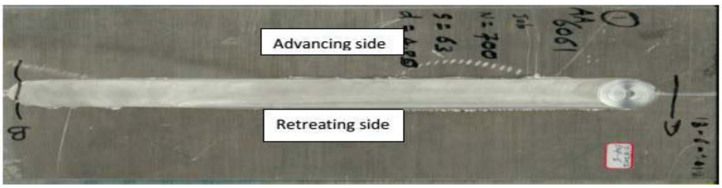

Figure 5(b). Photograph of FSW joint (retraced -Weld 3)

Based on the model developed for online monitoring of FSW process, to produce defect free weld, after noticing the defect, welding was stopped and tool was taken back and re- welding was done with little modification in FSW process parameters in the region where the defect had occurred earlier (Figure 5(a)). The screen shot of AE signal pattern acquired during retraced region is shown in Figure 8(a), wherein there was no sudden variation in RMS, Energy, Amplitude and Counts revealing the formation of defect free weld. The efficiency of welded joint at welded region was found to be 85.10 %, while at re - welded region it was 93.70 %. This variation may be attributed to refinement of grains in the re- welded region.

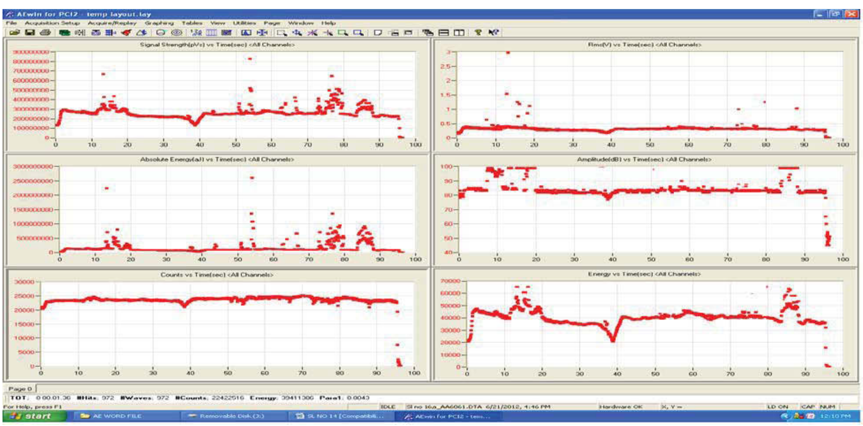

Figure 8(a). Screen shot showing AE signal pattern of different parameters during welding (retraced region of weld 3)

Conclusions

It can be concluded from the above studies that:

- AE technique can be effectively used for online monitoring of FSW process by suitably setting the threshold values of AE parameters to distinguish between good and bad welds.
- The model developed is helpful in identifying the occurrence of good and bad welds along with the suggested action to be taken to produce defect free weld.
- At location of defect in the weld, the process of retracing and re- welding was found useful in producing defect free weld with increased strength of welded joint.
- The threshold values of AE parameters considered for distinguishing between good and bad weld are specific to the material being welded, thickness of material and input process parameters considered.
- The outcome of results can be extended to other materials of different thickness during online monitoring of FSW process using AE technique after making repeatability and reliability studies.
- The inspection of welded joint is done during the process of welding itself, thus the productivity of the process can be expected to increase substantially.
- The inspection of welded joint using X-Ray radiography or any other method can be totally avoided.

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